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THE HIERARCHY OF FATIGUE MECHANISMS IN THE LONG LIFETIME REGIME (PREPRINT)

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THE HIERARCHY OF FATIGUE MECHANISMS IN THE LONG LIFETIME REGIME

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ABSTRACT

The primary factors governing the behavior in the long lifetime regime of turbine engine materials are discussed. These factors are based on a study of fatigue lifetime distributions and underlying mechanisms in a number of materials, including titanium alloys, nickel-base superalloys, and γ TiAl based alloys. A hypothesis of fatigue variability is described, and appears to explain the various features of fatigue behavior seen in the HCF and VHCF regimes. Central to the hypothesis is the proposition that a hierarchy of fatigue deformation heterogeneities develop in a specimen upon fatigue loading, which presents a finite probability of almost instantaneous crack initiation (and therefore, a limiting lifetime) under any nominal microstructure and loading condition. A probabilistic calculation using computational microstructural volumes representing a duplex $\alpha+\beta$ titanium alloy was conducted in order to elucidate the nature of the relationship between frequency of occurrence and complexity of crack-initiating microstructural arrangements. Calculations demonstrated a steeply declining trend of frequency with increasing complexity of the arrangement. Qualitative insights into the probability distribution of heterogeneity levels gained by this calculation are discussed from the perspective of life prediction in the long lifetime regime.

KEYWORDS

Fatigue variability, hierarchy of deformation, heterogeneity distribution, life prediction

INTRODUCTION

Fatigue cracks are known to initiate by a variety of mechanisms. In metallic materials, the mechanisms can range from dislocation pile-up at a microstructural barrier via planar slip [1], to slip incompatibility between phases [2]; as well as non-crystallographic crack-initiation promoted by microstructural features such as non-metallic particles and pores [3]. Further, depending on the material and test conditions, a mechanism can occur either in the surface or the subsurface of a specimen [4]. While differences in mechanisms is expected between different materials (or different microstructures of the same material) and with respect to test condition, it is recently being recognized that failures can occur from multiple mechanisms even under a given microstructure and loading condition [5-7]. This is especially shown to be the case in the long lifetime regime [8].

Physics-based probabilistic life-prediction models are essential ingredients in the next generation of life management methods being pursued by the aircraft industry [9]. Furthermore, recent emphasis on Integrated Computational Materials Engineering (ICME) requires microstructurally-informed fatigue models that can then be integrated with material development and processing steps. However, the assortment of fatigue mechanisms, as noted above, limits a physics-based life prediction model to a specific set of material and loading variables. In particular, the existence of competing crack-initiation mechanisms in the long lifetime regime under nominally the same set of variables increases the uncertainty in life prediction. On the other hand, there are some common physical principals that seem to govern the distribution in lifetime across materials and test conditions of interest, which may provide a pathway for a more broadly applicable life prediction method. This clearly demands a good understanding of those common factors that underscore fatigue variability in these materials.

This paper is motivated by the above questions. Towards addressing these questions, first, a discussion of common factors that appear to govern the fatigue lifetime distribution across several turbine engine materials and microstructures, under a range of relevant loading conditions, is discussed. Second, a hypothesis for the observed features of lifetime distribution is proposed. Third, a probabilistic calculation is presented that elucidates the relationship between the probability of occurrence and the complexity of crack-initiating microstructural configurations found in Ti-6Al-2Sn-4Zr-6Mo (Ti-6-2-4-6), an $\alpha+\beta$ titanium alloy. Results of the calculation are discussed in light of the proposed, hierarchy-based hypothesis of fatigue variability.

COMMON FACTORS GOVERNING THE FATIGUE LIFETIME VARIABILITY

A summary of factors that have been found common to the fatigue variability behavior of a number of turbine engine materials is presented here. Further details have been reported elsewhere [5-7]. The materials that have been studied include titanium alloys [5], nickel-base superalloys [6], and γ-TiAl based alloys [10]. The key features of fatigue lifetime distribution, common to each of these materials, are schematically illustrated in Fig. 1 [7]. As depicted in the figure, under relevant loading variables, the following factors appear to control the fatigue lifetime variability [5-7]: (1) mean and life-limiting (or minimum) behaviors separate (or converge) with respect to stress level (or any other variable), (2) the life-limiting failure population is largely controlled by the small + long crack growth lifetime, i.e., results from almost instantaneous crack initiation, and (3) the life-limiting behavior is produced by a more extreme microstructural configuration than the mean-lifetime-dominating population. The divergence of mean from the life-limiting response can be considered to be a consequence of different rates of influence of any given variable on the crack growth versus the crack-initiation regime. Therefore, a divergence of mean from the life-limiting behavior is suggested to occur whenever the crack-initiation lifetime is increasingly dominant in the mean behavior as, for example, with decrease in the stress level.

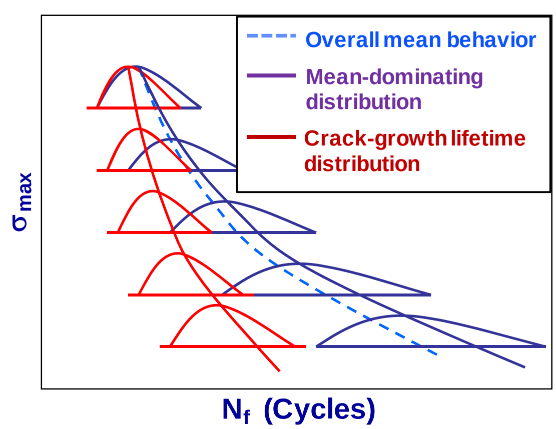

Figure 1. Illustration of the key features of fatigue lifetime variability in turbine engine materials.

In addition to the primary factors listed above, some secondary but equally important characteristics of fatigue behavior, especially relevant in the long lifetime regime, are suggested to be the following: (1) the frequency of occurrence of the life-limiting failures decreases with decreasing stress level [7], (2) fatigue cracks often initiate due to a combination of several microstructural constituents as opposed to an isolated microstructural unit [8], (3) there is a trend towards increasing frequency of subsurface failures with decreasing stress level [5, 11], and (4) the subsurface crack-initiation sizes or the underlying microstructural configurations are often larger than those that produce surface failures [8].

An understanding of the above factors is considered very important for accurately representing the effect of material and extrinsic variables on fatigue lifetime distribution. However, it appears that, although some current life prediction models address specific characteristics, there is a need for a more comprehensive approach which captures the key characteristics and underlying drivers of fatigue variability discussed above. This is particularly significant from a life prediction perspective as the above discussion suggests that a methodology based on variability about the mean lifetime may not produce an accurate estimate of the life-limiting response. Furthermore, since these factors transcend many materials, this also presents an opportunity for a more broadly applicable life prediction model.

HYPOTHESIS OF FATIGUE VARIABILITY

One hypothesis that may explain the key features of fatigue variability behavior displayed by a number of turbine engine materials is to consider that, under any nominal microstructure and loading condition, a hierarchy of localized deformation heterogeneities develops in the specimen. The distribution in magnitudes of these heterogeneities at a given cycle count is expected to take the form as illustrated schematically in Fig. 2. As depicted in the figure, higher levels of deformation will require an increasingly complex arrangement of microstructural phases, thereby the frequency with which such a configuration and the associated deformation can be found will be low. Similarly, smaller heterogeneity levels will have higher frequency of occurrence. Further, the crack initiation lifetime will increase as the magnitude of heterogeneity decreases, as indicated. In the figure, the approximated microstructural configurations found to initiate fatigue cracks in Ti-6-2-4-6 have been superimposed in order to provide a qualitative picture of where these configurations might plot on this probabilistic relationship. Further details on these microstructural arrangements and method of characterization have been reported elsewhere [8].

The probability distribution of heterogeneity levels, as depicted in Fig. 2, implicitly points to a finite probability of an extreme level of deformation that will produce almost instantaneous crack initiation. Of course, under certain conditions, such as in the VHCF regime, the probability of such an event may increasingly become small and therefore, a large number of tests will be required to capture that mechanism. This formulation also suggests that, for a given class of crack-initiation mechanisms, for example, strain accumulation in combinations of microstructural phases, all possible mechanisms might be represented by the probability relationship illustrated by Fig. 2. The implication is, that if the distribution of heterogeneity levels is accurately modeled, the probability of extreme, life-limiting cases can be determined even if a detailed information on the mechanism and the associated microstructural arrangement is not available (as is often the case due to the impracticality of running a large number of experiments).

The above hypothesis also appears to elucidate the main features of surface versus subsurface crack initiation observed in many materials. If the first crack is considered to initiate from the largest heterogeneity level, the subsurface volume being larger than the surface region, the largest heterogeneity in the subsurface is likely to be larger than the maximum heterogeneity in the surface (unless the specimen size is very small where the volume of the surface region begins to be comparable to that of the subsurface region). However, due to an essentially pseudo-vacuum condition in the subsurface, a larger heterogeneity level is required in the subsurface than in the surface to produce the same crack-initiation lifetime. Nevertheless, a competition between surface and subsurface crack initiation is expected at lower stress levels where the magnitudes of heterogeneities occurring in the surface are small enough for larger heterogeneity levels in the subsurface to begin dominating the failure. Note, that this hypothesis suggests a competition between surface and subsurface initiation rather than a sharp threshold for transition from one mechanism to the other. Second, this appears to explain the observation that a subsurface crack-initiation often occurs from larger microstructural configurations than a surface initiation.

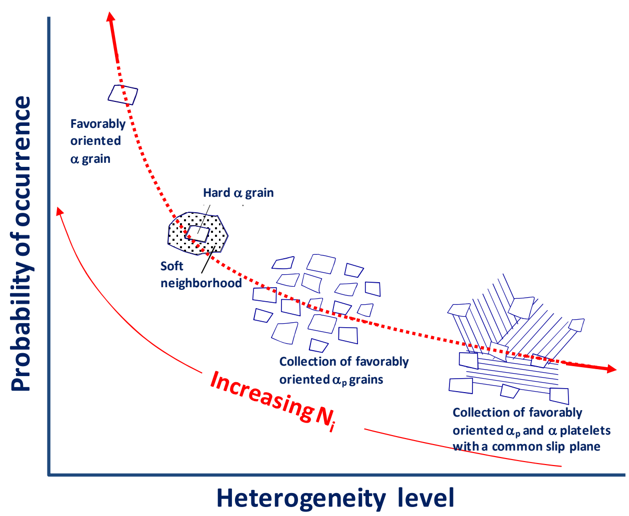

Figure 2. Illustration of the hierarchy of fatigue deformation heterogeneities. Schematics of crack-initiating microstructural arrangements estimated from characterization of Ti-6-2-4-6 specimens are notionally superimposed on the probability relationship.

PROBABILITY OF CRITICAL MICROSTRUCTURAL CONFIGURATIONS

In this section, a calculation of probabilities of occurrence of microstructural configurations that are known to produce crack initiation in Ti-6-2-4-6 is presented. These configurations were characterized by precision sectioning across crack initiation sites using Focused Ion Beam (FIB) and Electron Back Scattered Diffraction (EBSD) analysis on the sectioned planes [8]. The microstructural arrangements thus characterized are schematically depicted in Fig. 2. Note, that although these arrangements are based on inputs from characterization of crack initiation sites, idealized representations of observed characteristics are considered here. The configurations can be ranked in terms of their complexity or the presumed severity of deformation localization. In the order of low to high complexity, these configurations are: (1) a primary α (α_p) particle oriented for basal <a> slip (Schmid Factor for basal slip, $SF_{basal} > 0.45$); (2) a relatively hard α_p ($SF_{basal} < 0.35$) with all its first nearest neighbor grains favorably oriented for basal slip ($SF_{basal} > 0.45$); (3) a collection of α_p in which all particles, up to the second nearest neighbors to the central α_p, are oriented for basal <a> slip ($SF_{basal} > 0.45$); (4)

a collection of α_p and α/β colonies where all phases, up to the second nearest neighbors to the central grain, are oriented for basal <a> slip ($SF_{basal} > 0.45$) and the basal planes in each of the phases are aligned.

Synthetic 3D microstructural volumes were used in order to study the frequencies of occurrence of the above configurations. The microstructure model was based on the work of Przybyla, et al. [12] which employed the ellipsoid packing method. 3D cubical volumes of 400 μm sides were simulated. A two phase microstructure representing the duplex Ti-6-2-4-6 alloy was modeled. A 2D section, 400 μm X 400 μm, of a simulated cube is shown in Fig. 3(a). The colony was treated as a homogenized phase where the average size of the colony was 30 μm and that of α_p was 10 μm. The volume fractions of the colony and the α_p phase were 0.7 and 0.3 respectively. Total numbers of colonies and α_p in a typical simulated volume were about 514 and 5543, respectively. Grains were assigned random crystal orientations. The simulated volumes were then computationally interrogated for the crack-initiating microstructural arrangements.

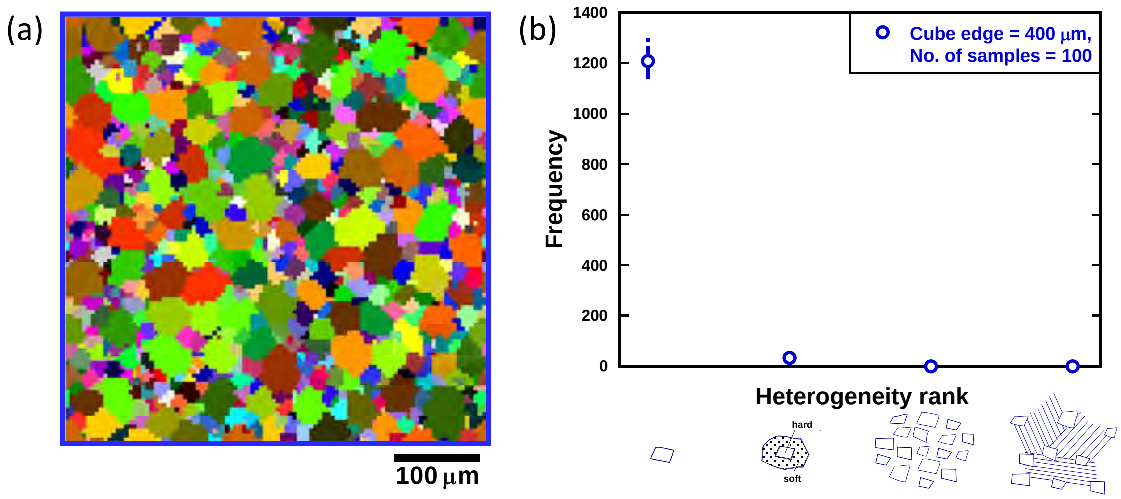

Figure 3. Relationship of the frequency of occurrence to the complexity of crack-initiating microstructural configuration in Ti-6-2-4-6; (a) a 2D section from a simulated microstructural volume and (b) calculated frequencies of microstructural arrangements.

Results of the calculation are presented in Fig. 3(b) where the average frequency of occurrence, based on 100 simulated specimens, is plotted for each configuration. As shown, the frequency displays a rapidly decreasing trend with respect to the complexity of the configuration. It is reasonable to suggest that the distribution in deformation heterogeneities in a specimen will follow a similar trend. In light of the hypothesis of fatigue variability discussed earlier, if the probability distribution of heterogeneity levels remains applicable across a full range of possible magnitudes, then this approach may provide a method of predicting the likelihood of crack-growth-controlled, life-limiting failures. However, it remains to be quantitatively shown if this probability distribution has a scale-free nature through the range of magnitudes relevant to life-limiting fatigue. Also important is the understanding of the evolution of the distribution in heterogeneity levels with respect to cycles, as this might determine the degree of separation between the mean and the life-limiting failures. Nevertheless, this result seems to point to some of the key features of fatigue variability discussed earlier. In particular, due to the rapidly decreasing trend of frequency with respect to complexity of the configuration, crack-initiation from larger configurations can be expected to occur in the subsurface. This is, of course, dependent on the specimen size where an availability of larger surface area will increase the probability of surface failures from larger microstructural configurations.

CONCLUSIONS

In this paper, a summary of salient factors underlying the fatigue lifetime distribution as a function of microstructure and loading variables in turbine engine materials was presented. The key contributor to lifetime variability was the separation of mean behavior from the crack-growth-controlled, life-limiting response. The hypothesis in terms of hierarchy of fatigue deformation heterogeneities provides an explanation for the fatigue variability behavior of these materials. A calculation of frequencies of microstructural arrangements, which are known to produce crack initiation in Ti-6-2-4-6, was performed using computational microstructural volumes and showed a rapidly decreasing trend in frequency with increasing complexity of the configuration. Although work remains to be done in terms of understanding the probability distribution of deformation heterogeneities and its evolution with time, a life prediction method based on this approach may hold promise towards accounting for the life-limiting failures in the long lifetime regime.

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